



# Overview – Materials for Distributed Generation

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#### **Distributed Generation Technologies**



## "Prime Movers"

#### 2000

- \$900-\$1,200/kW
- 17-30% Efficiency
- .35 lbs/MWh NOx



#### 2007

Cost competitive with the market

**Microturbines** 

- 40% Efficiency
- 2010 .15 bs/MWh NOx

- 29% efficiency
- +2 lbs/MWhr NO<sub>x</sub>
- \$600/kW
- 2001
- **38% Efficiency**
- 0.15 lbs/MWh NO<sub>x</sub>
- \$400/kW

#### 2010

Cost competitive with the market

Gas

**Turbines** 

<.15 lbs/ MWh NO.

#### 2000

- \$300-\$400/kW
- 25-40% Efficiency
- 2-3 lbs/MWh NO<sub>x</sub>

## Reciprocating

**Engines** 

#### 2007

- **Cost competitive with** the market
- **50% Efficiency**
- 0.15 lbs/MWh NO,

## 1992

# Materials Projects Support the Advanced Microturbine Contracts



- Collaborate with suppliers to develop advanced ceramics and evaluate the mechanical properties and environmental stability of candidate silicon nitrides
- Develop and evaluate environmental barrier coatings for monolithic silicon nitrides and advanced composites
- Develop creep- and oxidation-resistant metals for higher temperature recuperators
- Develop a microturbine test facility to evaluate new recuperator materials



# Near- and Long-Term Goals Have Been Identified by Microturbine OEMs

#### Maximum Materials Temperature Capability (°C)

600°C

650°C

700°C

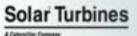
750°C

850°C

950°C









347 Mod 347 20/25 Nb



Candidate Materials are being evaluated in the Recuperator Test Facility







Haynes 120 Special Metals 803 Haynes 230 Haynes 214

2000

2002

2004

2006

2008

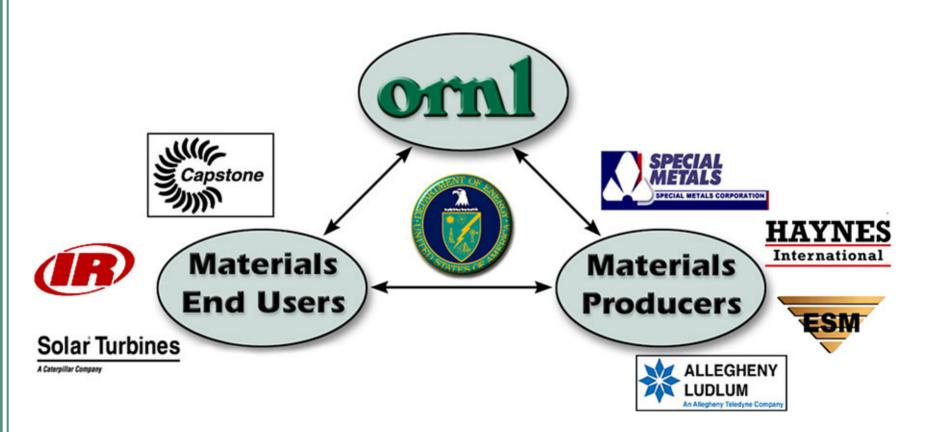
2010

2012

TIME (y)

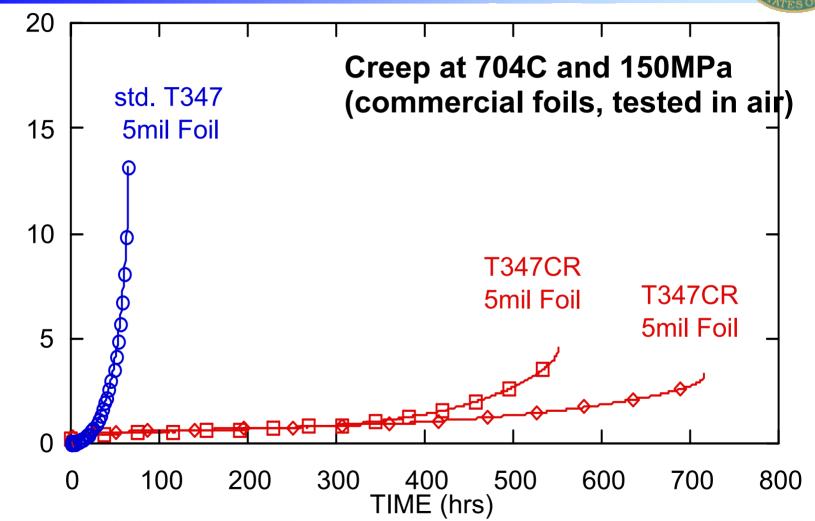
## Collaboration Between Materials Producers, End Users, and ORNL Has Spurred the Development of Improved Recuperator Foils

Materials R&D Capabilities and Expertise



# ORNL and Allegheny Ludlum Produced Creep Resistant Foils





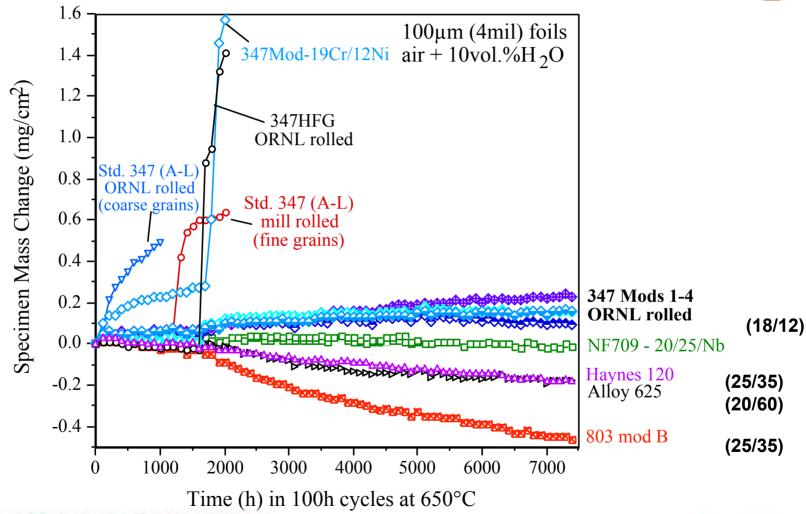
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CREEP STRAIN (%



# **Advanced Materials Require Improved Oxidation Resistance**

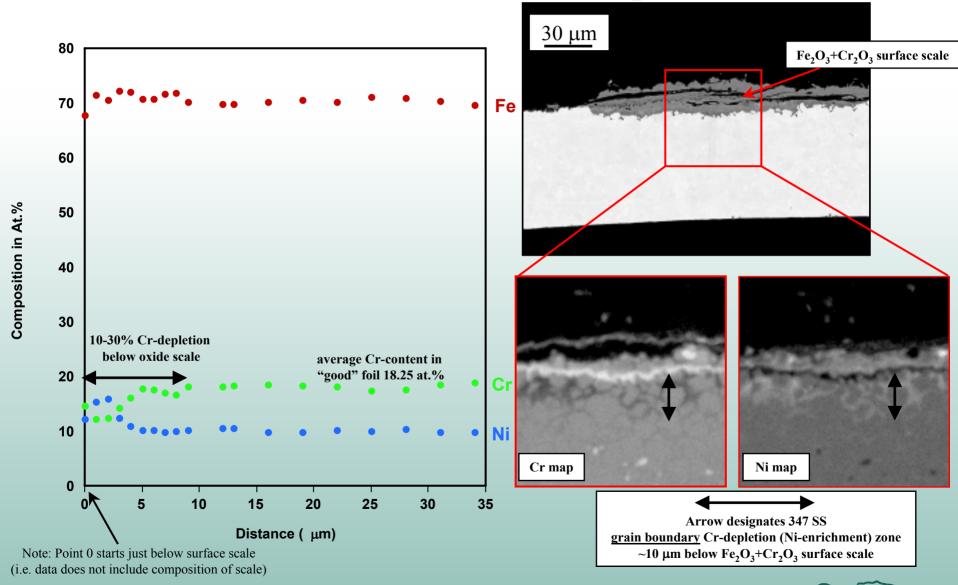




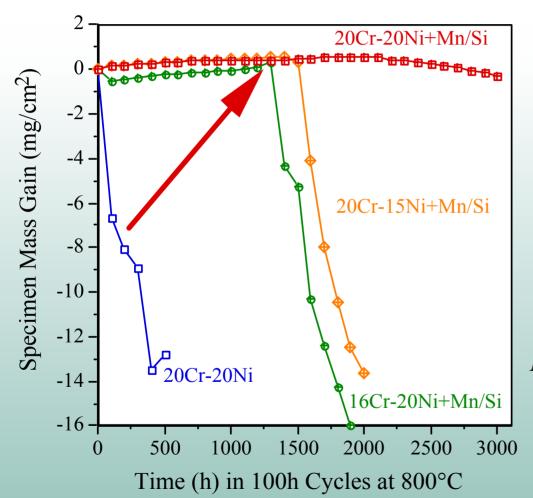
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# A Recuperator Engine-Exposed For ~19,000 h @ 1100°F Shows Near-Surface Cr-Depletion



## Model Alloys Are Being Used In The Development Of A Low-Cost Replacement For 347 SS With improved Temperature Capabilities



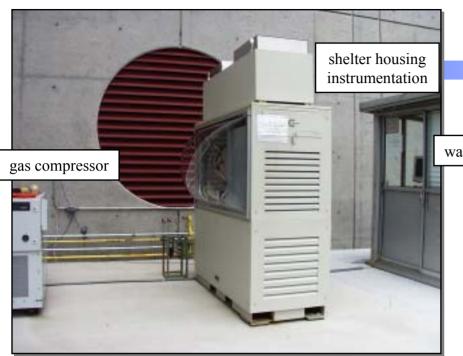
#### For Fe-20Cr-20Ni composition:

- Mn and Si appear to be most effective additions for oxidation-resistance
- However, if Cr- or Ni-content in base alloy is reduced, alloy becomes more susceptible to accelerated attack in water vapor

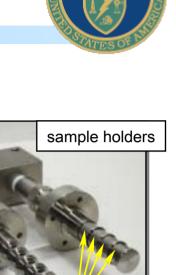
Next step is to modify Fe-20Cr-20Ni base to improve creep strength



**ORNL's Recuperator Testing Facility Is Operational** 



thermocouples sample holder water lines



• In collaboration with Capstone Turbines, a 60kW microturbine was modified to evaluate candidate alloys for the next generation recuperators.

- Six port bosses were incorporated around the microturbine vessel to allow the placement of test specimens at the entrance of the annular recuperator.
- The microtubine was modified to achieve turbine exit temperatures (TET) as high as 850°C.

stainless steel foil deformed by creep

sample holder after 500-hr test at 800°C

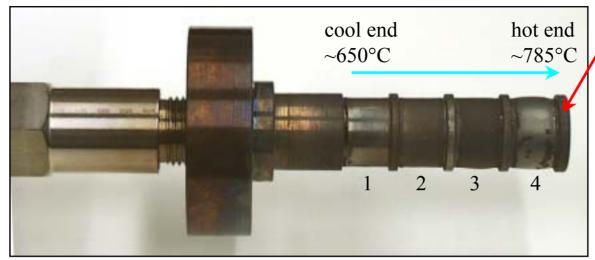
welded foils

Metallic foils are welded to sample holder and mechanically-stressed using compressed air

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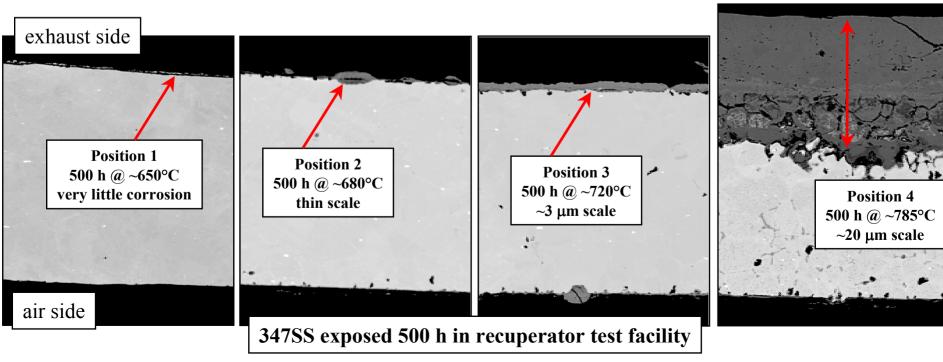
# High-Temperature Recuperator Alloys Are Being Exposed In A Modified Capstone Microturbine At ORNL



Fixture used to expose samples in ORNL's Recuperator Materials

Test Facility.

Foils are exposed to several different temperatures during exposure.



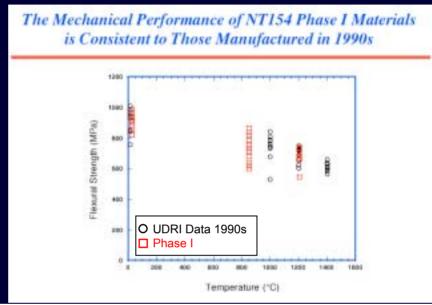
## Saint-Gobain Ceramics & Plastics

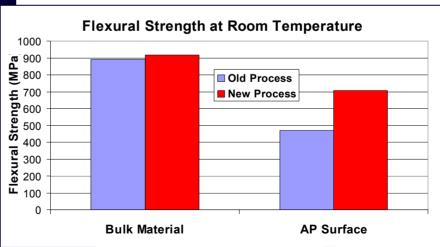
Material **Development** 

Forming Development

# ➤ Established and Improved NT154

- Reproduced historical NT154 silicon nitride properties using Closed Loop Process
- Demonstrated improved as-processed surface strength and finish
- Demonstrated improved high temperature strength 776 MPa @ 1200 C







## Saint-Gobain Ceramics & Plastics Dual Approach

## **▶** Net Shape Forming Development

Material Development

**Net Shape Forming Development** 

Developed green-machining process

 Green CNC Machining Direct Casting

- Completed demonstration axial rotors
  - Good surface finish
  - Uniform, isotropic shrinkage
- Currently producing full-scale radial rotors
- Improvements to direct casting approach

#### **≻Interactions**

- Cooperative R&D with ORNL
- Participated in DOE Technology Characterization
- Interactions with Microturbine manufacturers including Capstone, UTRC, and Ingersoll-Rand





# High-Temperature Materials are being Developed for Turbine Applications



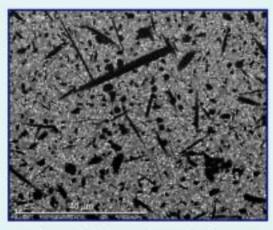
#### Kennametal

**Objective** – Modify and upgrade existing low-temperature sialon for turbine applications



Sialon cutting tool

- Component fabrication via low-cost sintering process
- Tailor sialon properties to meet demands of microturbine applications



β reinforced α sialon

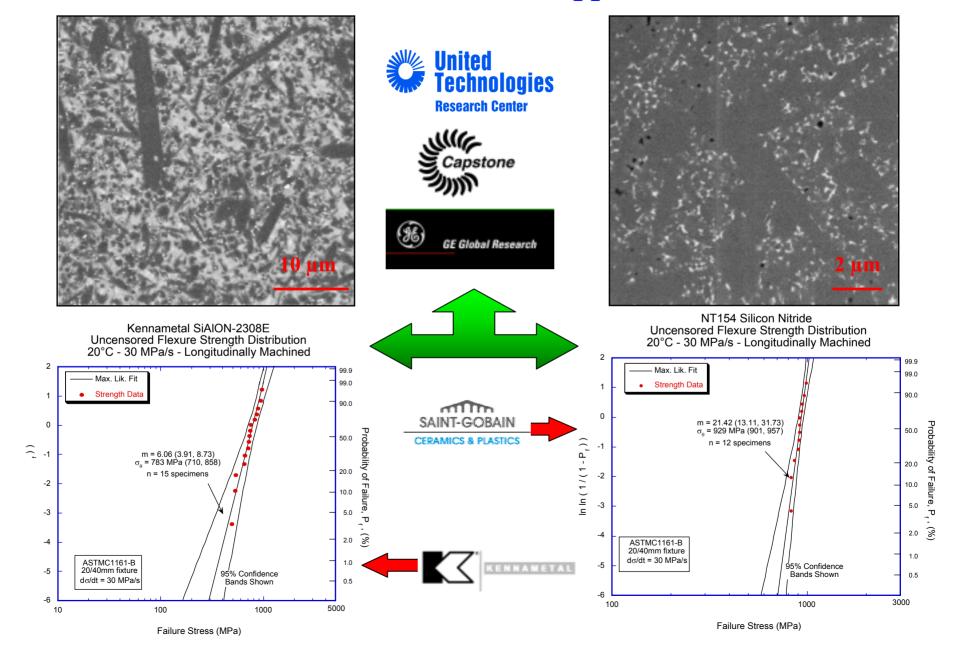
 Optimize grain boundary composition for improved environmental stability



# Monolithic Ceramic Characterization and testing

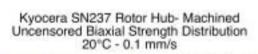
Oak Ridge National Laboratory
University of Dayton Research Inst.
Connecticut Reserve Technology
Argonne National Laboratory

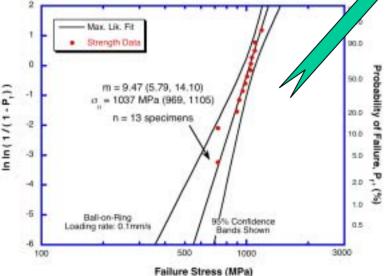
## Database Provided to Materials Suppliers & End Users



# Characterization of Components is Required for Life Prediction Assessment

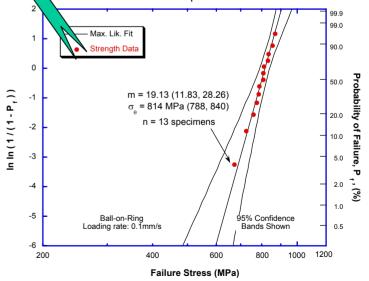








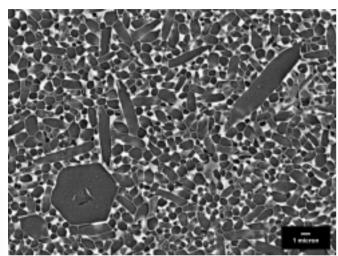
Kyocera SN237 - corrected Uncensored Biaxial Strength Distribution 20°C - 0.1 mm/s - As-processed Surface



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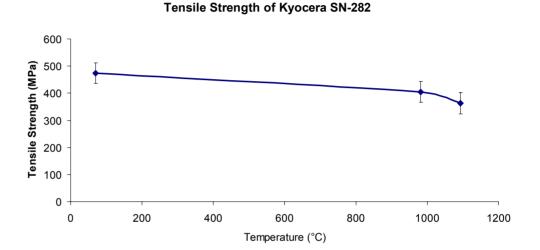


# Mechanical Characterization Effort at UDRI has Focused on Kyocera SN281 and SN282

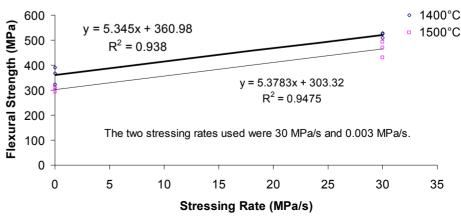


Microstructure of Kyocera SN 282 showing a mixture of high aspect ratio grains and smaller equiaxed grains.





Slow Crack Growth Study of SN-281
Shows Similar Dynamic Fatigue Behavior at 1400°C and 1500°C.
No Slow Crack Growth is seen below 1400°C

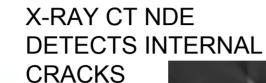


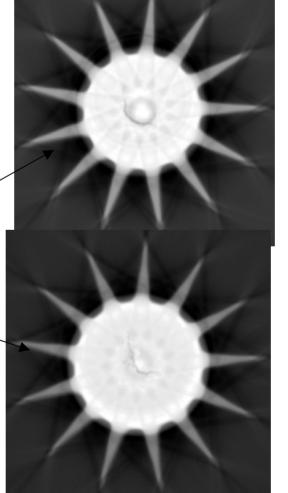


12 mm

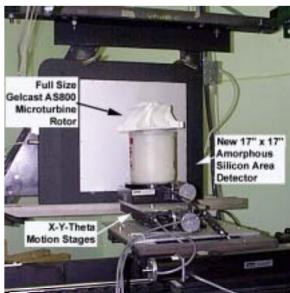
# ADVANCED HIGH SPEED COMPUTING HAS REDUCED 3D X-RAY IMAGING BY 10X FROM 480 MINUTES TO 40 MINUTES

PARALLEL COMPUTING FACILITY FOR HIGH SPEED IMAGE GENERATION





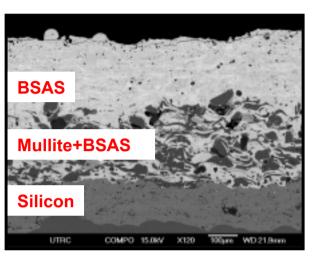




#### **EBC** for Silicon Carbide

#### BSAS based EBC<sub>SiC</sub> has accumulated > 40,000 hours at 2200F

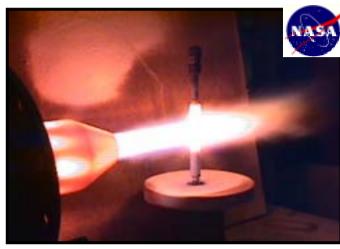




State-of-the-art EBC<sub>SiC</sub> system



CMC Combustor Liner with EBC<sub>sic</sub> (Solar Centaur 50S)



2700F Burner rig demonstration with 300F thermal gradient through EBC

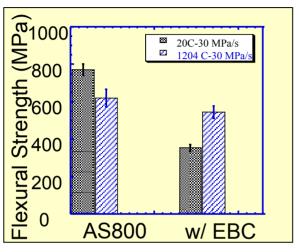
- ➤ EBC<sub>SiC</sub> has completed 15,000 hr field test in Solar Turbines Centaur 50S
- ➤ EBC<sub>SiC</sub> on monolithic SiC survived 100 thermal cycles in UTRC 2700F burner rig
- > Optimization underway to reach 30,000 life goal for IGT engine applications
  - Demonstrated coating refurbishment process
  - Identified top layer compositions with required steam stability
  - Advanced SAS based EBC<sub>SiC</sub> showing promise in on-going field tests



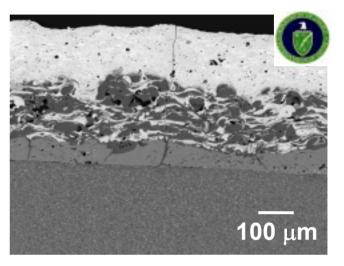
#### **EBC** for Silicon Nitride

#### EBC<sub>SiN</sub> being developed based on EBC<sub>SiC</sub> success





EBC<sub>SiC</sub> debits  $Si_3N_4$  strength ~ 50%; at 20C; ~ 15% at 1204C



 $EBC_{SiC}$  provided effective environmental protection to  $Si_3N_4$ 

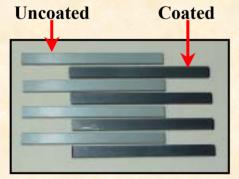
- > CTE mismatch is the key limitation of EBC<sub>sic</sub> to silicon nitride materials
- ➤ EBC<sub>SiC</sub> does provide effective Si<sub>3</sub>N<sub>4</sub> protection despite CTE cracking
- ➤ Promising approaches to develop EBC<sub>SiN</sub> have been identified
- ➤ EBC<sub>SiN</sub> system is being optimized for:
  - Bond layer adhesion to substrate
  - Chemical compatibility and stability
  - Thermal cycling durability
  - Substrate property retention



# Pack Cementation for EBCs S. D. Nunn and R. A. Lowden, ORNL

## FY2003 Accomplishments:

- Evaluated three Si<sub>3</sub>N<sub>4</sub> materials
- Studied coating in Ar, N<sub>2</sub>, & Air
- Prepared 12 pack compositions
- Processed at three temperatures
- Coated over 75 Si<sub>3</sub>N<sub>4</sub> samples



Pack cementation of AS800  $Si_3N_4$  bars in an Al -  $NH_4Cl$  -  $Al_2O_3$  pack at 1000°C for 5 hr. in Argon

#### **Processing Variables:**

- Pack composition
- Substrate composition
- Furnace atmosphere
- Temperature



#### **Silicon Nitrides for Pack Cementation Coating**

Si <sub>3</sub> N <sub>4</sub>	Additives	<b>Grain Boundary Phase</b>
Honeywell AS800	La, Y, Sr	La-Apatite
Kyocera SN281/2	Lu	Lu <sub>2</sub> Si <sub>2</sub> O <sub>7</sub>
Saint Gobain NT154	Y	$\mathbf{Y}_{2}\mathbf{Si}_{2}\mathbf{O}_{7}$

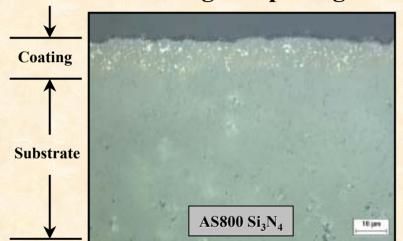


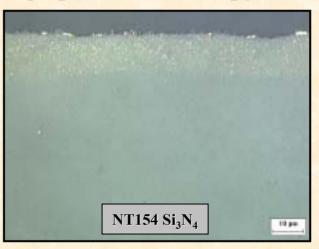


## Pack Cementation for EBCs

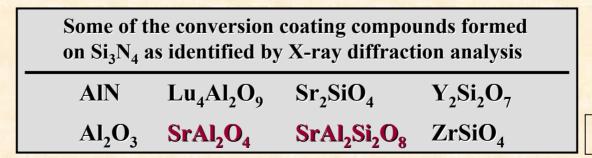
#### **FY2003 Accomplishments:**

• Evaluated coating morphologies using optical microscopy





• Identified coating compounds using X-ray diffraction analysis



Yb<sub>2</sub>Si<sub>2</sub>O<sub>7</sub>



# Key Materials Issues Will be Addressed in the ARES Program









- More durable / reliable NG spark plugs or ignition systems.
- Low-cost, rapid response NOx sensors.
- Low-cost materials for exhaust components.
- Low friction coatings for reduced wear

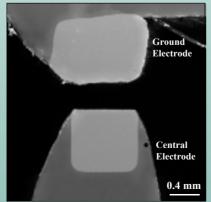


## Corrosion/Erosion of Spark Plugs

#### **Motivation**

- Advanced Ignition System is a key element in Advanced Reciprocating Engines.
- Corrosion/erosion of spark plugs limits the long-term reliability and performance of ignition systems and, thus ARES.
- Improvement of high-temperature corrosion/erosion resistance of electrodes is a critical issue to maintain the durability of spark plugs.





#### **Approach**

- Working with National Transportation Research Center
- Inspect, test, characterize field-tested engines
  - Received ~50 plugs from Cat, Cummins
- Identify erosion/corrosion mechanisms of ground and central electrodes
- Develop alloy to extend spark plug life



## DER Materials Program Addresses Industry Needs



#### Material Suppliers

(St.-Gobain, Kennametal, Honeywell) (Allegheny Ludlum, Haynes, Special Metals)

### Microturbine & Recip OEMs

(Ingersoll Rand, Capstone, GE) (Caterpillar, Cummins, Waukesha)

#### **Turbine OEMs**

(United Technologies, Solar, GE)



# Joint Effort Between Solar, Allegheny Ludlum, and ORNL Has Been Initiated



 To produce 5,000 lb batch of corrosionresistant 20/25 Nb and 20/20 foil

ORNL-modified processing to improve creep resistance

 Supply batch of foil to Capstone and Ingersoll-Rand



## Collaborative Project has been Initiated to Develop a Carbon Foam Heat Exchanger





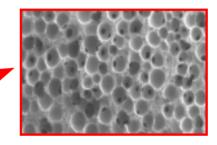
60kW Capstone µTurbine



Unifin

- MicroGen
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- Optimize design of carbon foambased heat exchangers for CHP systems.
- Evaluate optimize design and model predictions using ORNL's 60kW Capston microturbine and a modified Unifin Microgen.



carbon foam heat exchanger





# Keiser Rig Screens Ceramics, Composites & Coatings for Use in Turbine Hot Sections





- Temperatures up to 1500°C
- Pressures to 30 atm
- Low gas velocity (0.1 m/s)
- Water vapor pressures to 4 atm
- Up to ~60 specimens/run (multiple tubes)
- 1000's of hours of exposure

High-pressure, high water vapor contents are being investigated to simulate higher gas velocities

